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PARTICLE DISTRIBUTION IN THE OCEAN

BY

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distribution of matter suspended in the is intimately related to the production ing matter. The production problem in s bearings has been closely investigated by RILEY, STOMMEL, and BUMPUS (1949) ie Western North Atlantic and by HARVEY) for the sea off Plymouth.

filtration of the water samples and mination of dry weight it is possible to n a measure of the total amount of nded particles. ARMSTRONG and ATKINS) have used this procedure, combined an inorganic analysis of the ignited dry er. KREY (1949) has developed a simple od of filtering particles according to size, wed by a microscopic analysis. In addition, neasured the content of clorophyll and men in the suspended matter in order to e at a qualitative and quantitative control e decrease or increase of its organic content. ving organisms constitute a considerable of the total content of particles in the r strata in the ocean. But dead organisms play an important role. When sinking remains of plankton, the *detritus*, are ually decomposed. For the upwelling r west of Africa WATTENBERG (1937) has wed the different stages of the disintegra- process. Inorganic matter derived from or from the bottom is present to some unt in the ocean. By currents and hori- al eddies fine material can be transported away from shore, and air-borne terrigenous is an important contributor to the particle ent.

hus, the suspended matter has many components. The biological interest is chiefly focussed on the plankton and on the upper, illuminated strata, whereas the geologists pay more attention to particle distribution near the ocean floor. From a hydrographical point of view the question has a somewhat different aspect, as the distribution of suspended matter in the whole water column is significant. Particles affect both physical and chemical conditions in the water, in the first place the optical conditions. These effects have been discussed by KALLE (1943).

Optical Characterization of Ocean Water

The marked influence of suspended matter on light suggests the use of optical methods for studying the content of particles in the ocean. Several optical methods have been employed for characterizing the water of different ocean areas. It is relevant to take a quick survey of the various alternatives.

1. *Observation by Secchi disc.* This gives a rough measure of the transparency of the water down to the depth where the disc disappears from sight. Formerly widely used it is nowadays mostly abandoned for more satisfactory methods.

2. *Study of the colour of the sea.* The colour of the sea has been roughly determined by comparing the colour of the submerged Secchi disc to the »Forel scale». More accurate investigations have been made by means of special devices (KALLE, 1938). Naturally the colour stands in a certain relation to the transparency of the surface stratum of the sea.

In the first place the colour shows the amount of dissolved yellow substance which is responsible for the shift of colour from the natural blue towards the green (KALLE, 1939 a).

3. *Measurement of subsurface radiation in the visible and in the ultra-violet.* Observations of daylight can be carried out by simple photoelectric means down to 200 m in the ocean. In still deeper water photographic methods, though laborious, are more suitable. Some difficulties are involved in the photoelectric method. When a photometer is provided with colour filters there will often, with increase of depth, occur a shift of the centre of gravity of the measured radiation due to selective absorption by water. The extinction of daylight by sea water is made up of absorption (caused by the water, by dissolved substance, and by particles) and a *fraction* of the scattering (caused by particles) (see v. III, p. 26). Moreover this fraction varies with the depth (LE GRAND, 1939). Observations of submarine daylight are of biological importance as they afford us with data about the supply of the radiant energy present at different levels which can be utilized for maintaining photosynthesis. The ultraviolet radiation which is active in the production of vitamin D is also significant from a biological point of view. In characterizing the water, the penetration of the ultra-violet gives a very sensitive measure of the content of yellow substance (JERLOV, 1946)

4. *Transparency measurements in situ* (H. PETTERSSON, 1934). The transparency to a beam of electric light is measured by means of a photocell. The direct measurement *in situ* has the advantage of allowing a study of the continuous alteration of the transparency with depth, so that a microstratification can be detected. Because of the short light-way in the water (so far at most 2 m), extinction values obtained by the transparency-meter are not very accurate, and, though useful in coastal water it is not the proper instrument for the ocean where the transparency is subject to small alterations both horizontally and cally. When standardized (JERLOV, the transparency-meter records the tru tinction *i. e.* the sum of absorption and sc ing. Transparency measurements alone, if made for different colours, do not fu sufficient data to distinguish betwee extinction due to particles and that d dissolved substances, as the absorptio particles as well as the absorption by y substance exerts a selective action o transmitted light.

5. *Transparency measurements in vitr* MES and BIRGE, 1938). The extinctio water samples is determined by means monochromator. The accuracy of this la tory method is subject to the same limitat the observations *in situ*. By filtering the sample it offers a possibility of distingui between the extinction due to particles that due to dissolved matter (JAMES and B 1938; CLARKE and JAMES, 1939). As preservation of water involves difficultie necessity of field observation must be e sized. The procedure is, however, too labo to be used conveniently in routine work a

6. *Scattering measurements in situ.* (H. TERSSON, 1934). The scattering of a be artificial light in the water is measur means of a photocell. The results give a ure of the concentration of suspended pa but also are in a complicated way affect the extinction. The scattering-meter is sensitive to daylight in the water and s preferably be used at night.

7. *Determination of the content of pa by studying the Tyndall effect in water sa* This method, which aims directly at dete ing the amount of suspended matter, introduced by KALLE (1939 b). A si method was developed and employed d the Swedish Deep Sea Expedition. Me ments of the particle content in the samples were accordingly included in hydrographical routine work on board.

Tyndall Meter

he device for measuring the intensity of Tyndall beam is a Zeiss turbidity meter 1 some technical modifications. Since the 1 transparancy of the samples requires an nse light source the electrical lamp in the inal apparatus is exchanged for a slit lth 1 mm) illuminated by a carbon arc s. 1 and 2). A parallel Tyndall beam is jected into the sample, contained in a ll glass flask (60 ml) and placed in a chamber d with water. The intensity of the light ttered from the Tyndall beam at an angle 45° is measured by means of a Pulfrich otometer. A scattering glass, against which ie of the initial light is reflected, serves as a aparison. Low-scattering samples are com- ed with a slightly etched glass, those of dium scattering power with a more strongly hed glass, and high scattering samples with a kglass. The photometer is provided with a filter (centre of gravity 615 mμ), a green er (535 mμ), and a blue filter (470 mμ).

During the expedition the Tyndall meter

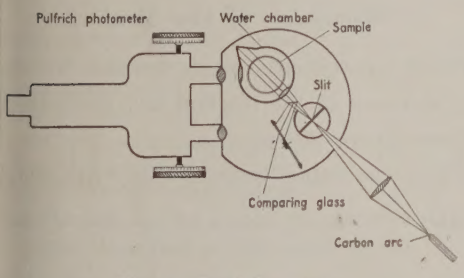


Fig. 1. Tyndall meter.

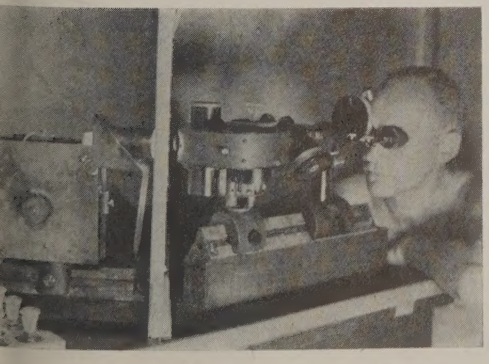


Fig. 2. Measuring the Tyndall effect.

was placed in the optical darkroom. An asbestos wall protected the observer against light from the carbon arc. For the clearest samples it was necessary to work with completely adapted eyes. Then, the accuracy realized by the Tyndall reading is the same as that normally obtainable with the Pulfrich photometer (see URBACH, 1937).

Procedure

The method, if also to be employed with clear ocean water, demands great care to avoid contamination at the collection of samples, and also that the samples are studied before any change of the particle content has had time to occur.

For collecting samples at subsurface levels Knudsen's water-bottles were used. As the nickel-plated interior of the bottle is likely to contaminate the enclosed water, it is advisable to coat the inside of the bottles with ceresin. The protective effect of the ceresin was checked by the author in the following way. An iron vessel with fresh rust was lined with ceresin. The transmission of double-distilled water to blue light did not show any measurable change after the water had been shaken in the vessel. Not only the metal parts including the central spring but also the rubber packings could be lined with ceresin without preventing the lids from closing properly. Although the central spring is stretched and slackened when the bottle is used, its ceresin coating did not show any flaws.

When the water bottle was brought on board a sample was drawn off into a small glass flask with a ground stopper. The flask was cleaned externally with 50 % alcohol and placed in the Tyndall meter, where the tests were run. During the measurement the flask was kept rotating round its vertical axis, in order to eliminate the influence of small optical irregularities in the glass. The turning round also served to stir up big par-

ticles from the bottom. The water chamber was frequently refilled with clear deep-sea water.

The intensity of the Tyndall beam was determined in the blue and in the red, sometimes also in the green, three times for each colour.

Standardization

It is worth while to ascertain whether the intensity of the Tyndall beam in a 45° direction represented by the Tyndall reading could be expressed in a known unit like the scattering coefficient. The extinction of a beam of light by sea water is the sum of absorption and scattering. For the ocean the scattering coefficient attains only low values, and so it is proportional to the amount of light lost by scattering. The problem of scattering by particles suspended in water has been treated for instance by BLUMER (1926) and by LE GRAND (1939) under the assumption that the particles are spherical and transparent.

However, the ocean contains particles of different kinds, and it is, therefore, necessary to determine by experiment the ratio of the total scattering coefficient S and the Tyndall reading A. Table 1 is prepared to show this

TABLE 1. Ratio of total scattering coefficient S to Tyndall reading A for blue light (470 mμ)

Station	S/A
29	0.00046
46	54
108	62
111	51
123	50
338	50
371	53
Mean value	0.00052

ratio S/A for blue light and for different stations. The readings A were determined with the low-scattering comparison glass. The values of S were derived through comparison between daylight measurements and transparency measurements (JERLOV, 1951).

In view of the accuracy attainable in det nations of S the variations found in are unimportant and may be disrega the ratio may be considered as a consta 0.00052. In the total scattering S the scatt by the water itself (0.003 m^{-1} at 470 m also included. Hence the scattering ca by particles only, s, conveniently expr in km^{-1}, is found by the formula:

$$s = 0.52\,A - 3$$

Too much emphasis should not be pl on the absolute value of s, which ultim depends on the standardization of the trans ency-meter. Strictly speaking, the a expression is valid only for the upper st The question if it holds true also for water must be left open. There is every re to believe that the deviation is not import

In the ocean the scattering by part predominates over the absorption by part and dissolved substance. Thus the Tyr effect could be given almost as well in ex tion coefficient as KALLE (1939) has don

Discussion of the Method

Some experiments were devised to cl the accuracy of the method and delineate necessary precautions.

From the same water bottle two sam

TABLE 2. Scattering values s for two samples tak different flasks from the same water bottle

Depth m	s
145	68
	60
185	55
	57
344	56
	56
440	55
	55
538	50
	54
728	50
	53

e taken in different flasks. A comparison veen the two s-values for various levels in le 2 shows the normal uncertainty in the rmination of s. Table 3 embodies results

LE 3. Different ways of filling the flask from the water bottle

Technique used	s
ober tube at the tap, the first water of he bottle	33
ober tube at the tap, the last water of he bottle	35
sk close to the tap	31
ne distance between flask and tap	30

n different ways of filling the flasks from water bottle. In this case the bottle tained water from 2,500 m. In routine k the filling was made with the flask quite e to the tap.

n order to demonstrate how easily the ples can be contaminated (Table 4) an air

TABLE 4. Influence of air dust on the samples

Treatment	s	
	before	after
mple shaken with an air bubble from the laboratory	41	54
mple shaken with an air bubble from the deck	41	44
mple left open for three minutes in the laboratory	27	42
mple left open for three minutes on the deck	24	31

ble was introduced into the flask which s shaken afterwards. The pure air taken m the deck did not affect the sample to any asurable degree but the laboratory air, ng full of dust, spoiled the sample. Likewise the flask was left open for three minutes ugh dust enters it to raise the s-value reciably. The clarity of deep-sea samples illustrated by their low s-value of 20 quently found, whereas distilled water in laboratory gave $s = 60$.

It remains to consider the change with ne of the particle content in the sample. In some cases a sample was studied immediately and a control sample of the same water was left standing during 12 hours without exposure to light before the measurement. The change in s was from 39 to 41 (mean of three samples), *i. e.* negligible. But, if water is left in the water bottle for a day the particle content will decrease considerably because particles settle. A similar decrease occurs in a sample for which tests are run repeatedly. Table 5 based

TABLE 5. Average decrease with the time of scattering s in a sample

Hours	s				
0	25	50	75	100	125
2	25	49	73	96	116
4	24	48	69	89	106
6	23	44	63	80	94
8	21	40	56	70	78
10	21	39	52	63	67
12	21	39	51	59	61

on observations in the Indonesian seas shows the average decrease with time of different s-values. The reduction is only slight for clear water but rises to as much as 50 % for turbid samples. This decrease is caused by particles being disintegrated, associating with each other, or adhering to the walls and to the bottom of the flask, so that even a rapid rotation does not bring them into suspension. Apparently the effect in question is accelerated by irradiation.

As a precaution it is advisable to make measurements as soon as possible after the sample is taken.

A possible objection against the method concerns contaminations from the wire which is in close proximity to the water bottle. There is no reason to believe that the wire could supply the water sampled with an additional amount of particles. Loose particles on the wire, not being washed away when the wire runs through the water with a speed of three meters per second, are not likely to become detached at rest. At the hydrographical work the wire was at times rusty but among

the numerous samples taken only a few were found to contain red or brown particles indicated by a higher scattering of red than of blue light. However, in these cases it is much more probable that the coloured particles are inherent in the water (see below).

It may also be mentioned that, when the wire had been oiled, scattering values found before and afterwards did not differ appreciably.

The method described here yields information about the particle content at definite depths in the sea. Sometimes there is — as stated by observations — a stratification in particle distribution between these levels. This would suggest that it is more suitable to measure *in situ*. However, it meets with certain technical difficulties to devise an apparatus for measuring *in situ* and by daylight.

Observation Material

No plankton biologist was included in the scientific staff onboard. Neither was any systematic collection and analysis of biological material accomplished. Naturally it is a great disadvantage that these measurements, in particular for the upper strata, lack the support of biological data: therefore, a correlation between the total content of particles and the amount of plankton at different levels could not be made. The available material of particle observations is here treated chiefly from a hydrographical point of view, in order to find evidence for water movements. Several points concerning the relationship between particle distribution and chemical data are left open. The chemical problems in deep water are being subjected to a close examination by Koczy (v. III).

The s value computed from particle observations are set out in Tables of Physical and Chemical Data (v. III, No. 4). Diagrams prepared for various stations and sections are used in the following discussion.

Size and Colour of Particles

In the routine work the Tyndall effect the water samples was determined for blue well as for red light. As a rule, the for values were found to be somewhat higher t the latter. If the constant selective scatter by the water itself is deducted, the resid deviation between computed s values for blue and for the red amounts to about 5—10 Thus, the scattering caused by suspen particles is only slightly dependent on wave-length of the light (cf Jenkins a Bowen, 1946). This suggests that their in general equals or exceeds 1 μ whereas fi material is of minor importance. The min particles in the bottom sediments have median diameter of 7—8 μ in globigerina diatom oozes, and of 1 μ in red clay. The f clay present above the bottom in suspens is likely to exert a selective action on li but this may be reduced by an opposite col effect.

Big particles above 1 mm were occasion present in the samples but were never obser in the deep-sea samples.

The method as far as it is developed d not give much information about the distribution of the particles. The effect size could be obscured by the effect of colo the suspended matter in the ocean being of coloured. Very rarely, the existence of red brown particles could be ascertained as indic ed by a higher scattering for the red than the blue. In these cases the colour was direc visible to the eye. For instance, close to bottom (181 m) at station 247 in the Red a red suspension was found, which was possi due to remains from red algae. Observati of brown matter were also made at Station between 500 and 1,500 m and at the adjac Station 108 at 600 m only. There is no obvi explanation of this localized phenomenon

As the scattering is practically non-select the s-values obtained give an approxim

sure of the total particle surface (DALLA LE, 1948). The relationship between scat- ng and mass per unit-volume is dependent particle size. In water rich in nutrients the kton is on an average of larger size than ess fertile areas. Therefore, for a given tering, the mass is higher in the former n in the latter case. The problem of the ribution of suspended mass deserves further ntion, in particular from a geological point iew.

hen sinking, the dead material is sorted ording to size. The big particles take a ter time for sinking whereas the very fine erial may remain suspended for years. he following discussion it must be observed small particles — though not smaller than micron — play the greater part of the ended material in deep water.

Submarine Slopes

ome interesting features in particle distri- ion are found at localities where different es of water meet over a relatively shallow ing bottom.

As an illustration two vertical sections of particle distribution off the Nile delta are shown in Fig. 3. Three stations, 261—263, fall within the easterly section, six stations, 266—271 within the westerly section.

Judging from observations of temperature and salinity the salt Mediterranean water is mixed with the Nile water, and no stratification is found. The temperature shows a slight decrease with increase of depth. The salinity in the shallow water ($\backsim$ 38.9 ‰) also seems to be a little higher at the surface but the deviation is nearly within the limits of accuracy of the observations. On the other hand, conditions at Station 263 are typical for the eastern Mediterranean, the intermediate water exhibiting at 150 m a salinity maximum of 39.13 ‰.

From Fig. 3 it is seen that the large amount of debris carried by the Nile flocculates and settles rapidly. Thus already some tens of miles from the coast the water is practically free from particles from the river. The western section shows clearer water than the eastern due to transportation of debris eastwards by the prevailing current.

The slope of the bottom characterized by

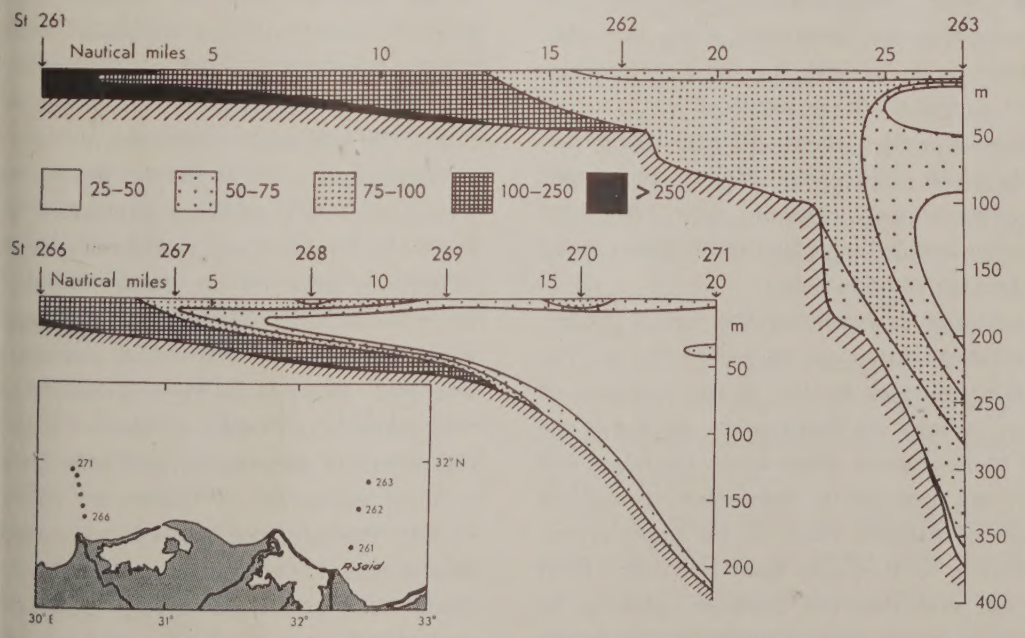


Fig. 3. Particle distribution in two vertical sections off the Nile delta.

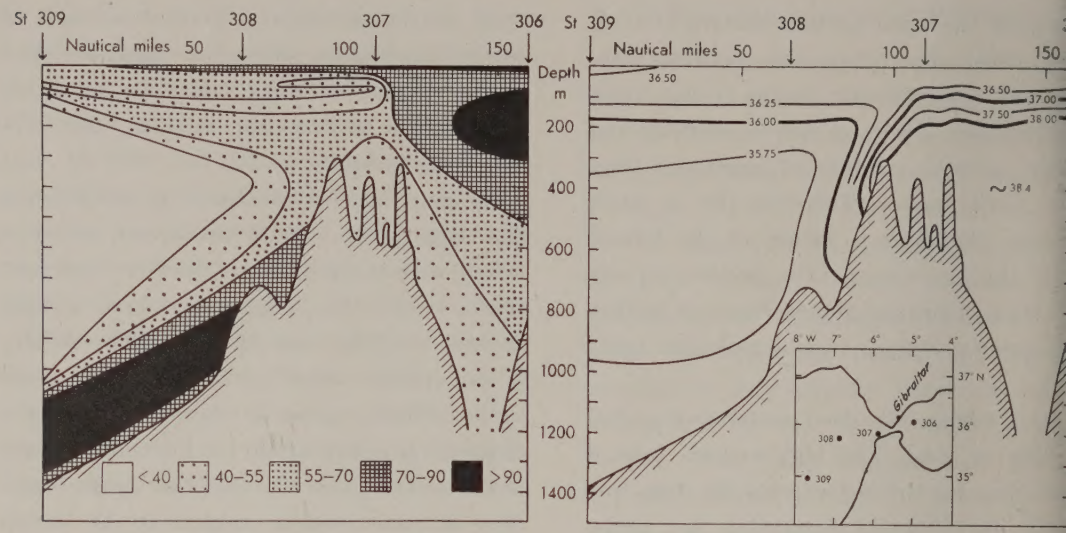


Fig. 4. Distribution of particles and salinity in a vertical section through the Strait of Gibraltar.

ledges becomes very steep towards Station 263. Here the turbid water is detached from the bottom and is present as a tongue at 250 m, whereas the water close to the bottom is clear. The content of particles in the surface water is already normal, and the very clear Mediterranean water is found at 25 m and at 100—200 m. It is consistent with earlier experiments (GRIPENBERG, 1934) that the flocculated units, produced when fine clay material is mixed with sea water, settle relatively slowly (1—20 m per day).

Another section shows particle distribution in the Strait of Gibraltar (Fig. 4). It is based on observations made on June 12th 1948 (Stations 306, 307, and 308) and in the morning of the 13th (Station 309).

Isohalines representing the actual hydrographical situation are set out in Fig. 4. The well-known main feature in the exchange of water through the Strait is the sinking of the salt Mediterranean water across the ridges and down the shelf and its replacement through an inflow of Atlantic water in the upper layers. According to RAMALHO and DENTINHO (1931) the salt water does not, however, spread so far to the south as Station 309. Further details about the water exchange through the St have been given by SCHOTT (1928) who st that the rate of inflow is of medium stre in spring.

The superimposed tidal currents do not p any important role at Stations 306 and which were made at low tide. But Station was occupied three hours after low tide in this case the inflow of Atlantic wate greatly reduced which is consistent with salinity distribution found at this locality.

As regards the particle distribution in Strait, the following features are noticed. Mediterranean water at Station 306 is cha terized by a rich plankton population in surface water but there is also an abunda of particles round 200 m. On the Atlantic the water is fairly poor in particles, except layers near the bottom, which contain l amounts. There is no obvious connectio very turbid water between these two large centrations of particles on each side of the no deep level at Station 307 attains an *s*-v of 70. Possibly the observations may h missed a cloud of particles at some interme depth but the intense mixing in the St evidently favours a more homogenous di

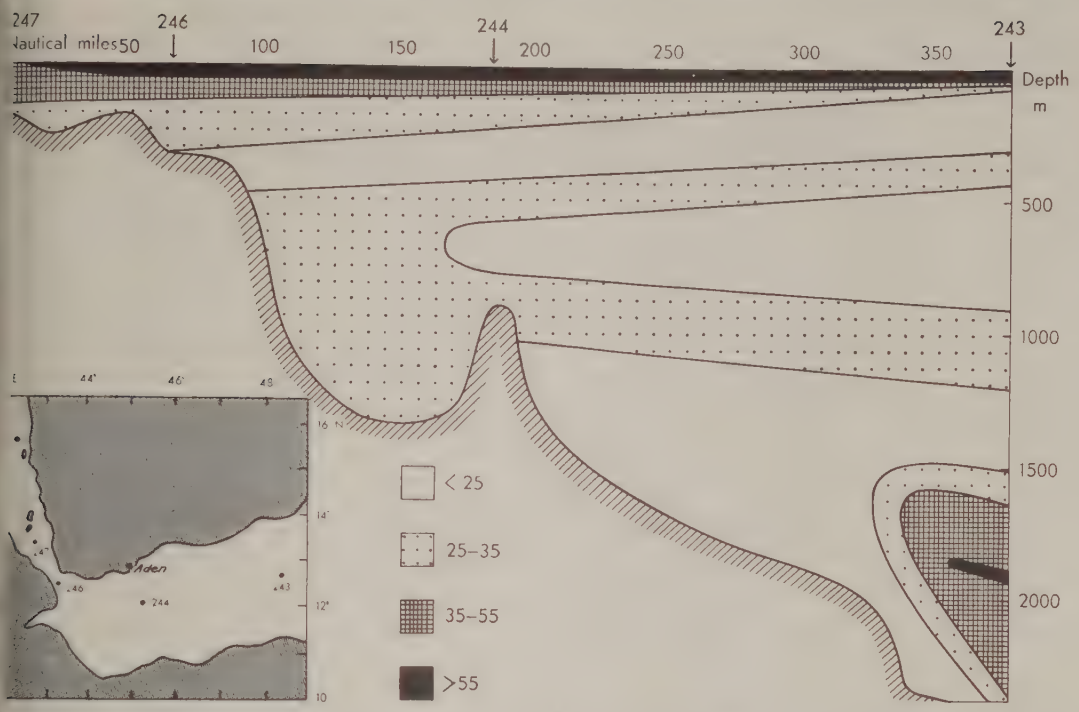


Fig. 5. Particle distribution in a vertical section through the Strait of Bab el Mandeb.

tion. This is also supported, for instance, vertical phosphate distribution.

Summing up, we may say that the exchange mechanism carries particles with the Mediterranean water across the sill to the bottom layers on the Atlantic shelf, in particular when the tidal currents are favourable for a strong bottom current being developed. But the trend of the 36 ‰ isohaline indicates that to some degree a downward transport of Atlantic particles also takes place.

In the Strait of Bab el Mandeb a similar exchange mechanism operates which is, however not well developed in spring. Hydrographical observations were carried out from the »Albatross» in April 1948. The high salinity near the bottom at Stations 244—247 indicates that very saline Red Sea water flows out over the sill. The particle distribution (Fig. 5) is fairly uniform but there is a small concentration of material above the bottom at Station 243 analogous to conditions on the Atlantic side of the Strait of Gibraltar.

Equatorial Currents

A large amount of the total particle content in the upper layers is made up of living organisms. The phytoplankton sink below the compensation point, die, and at deeper levels reach various stages of decay. We shall not enter into a discussion of all phases of this problem. It should only be mentioned that the water temperature has a high effect on the sinking rate of particles because the viscosity is reduced with increase of temperature. Thus, the sinking velocity of small particles is 30 % higher at 20° than at 10° (Brinkmann, 1931). — The distribution of zooplankton is also controlled by environmental factors. Besides, a restricted migration under directing stimuli such as light and gravity plays a role.

In the equatorial areas the distribution of suspended matter is largely determined by water movements associated with the system of equatorial currents. Abundance in phyto-

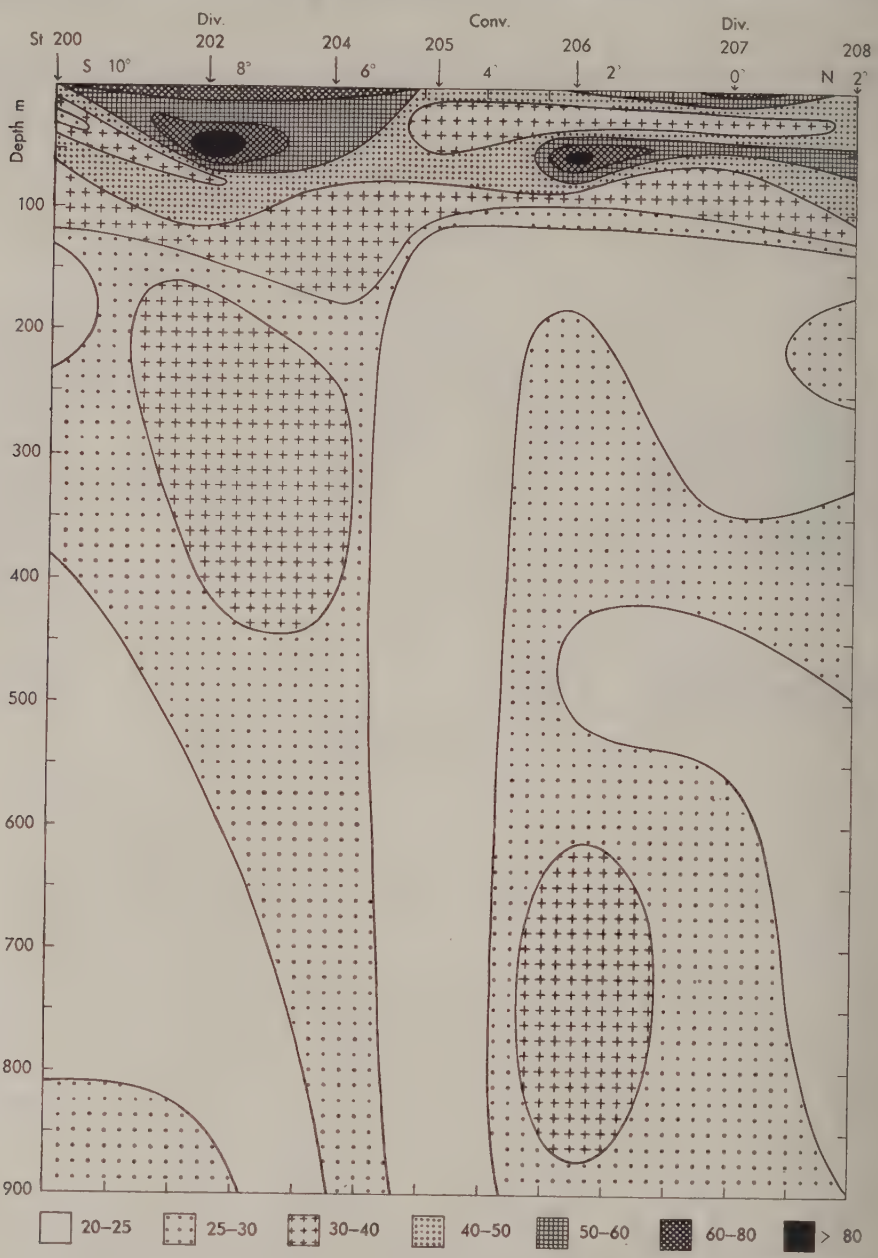


Fig. 6. Vertical distribution of particles between Stations 200 and 208 in the Indian Ocean.

plankton is apt to occur where a rich supply of nutrients takes place. As the ascending water brings plant nutrients into the illuminated zone, the regions of divergence will be regions where large phytoplankton populations may be expected. Conversely, regions of convergence, where the water descends, may be expected to be poor in phytoplankton. These conditions have earlier been demo strated by HENTSCHEL (1928) for the Sou Atlantic and by GRAHAM (1941) for the Pacif Countercurrent. They are clearly illustrat in our results from the Countercurrent in t Indian Ocean.

Fig. 6 shows the particle distribution in vertical section near 88° E across the syste

equatorial currents in the Indian Ocean. ording to dynamical deductions on the s of serial observations onboard the »Alba-s», the divergence between the South atorial Current and the Countercurrent is developed and observable at Station 202 veen 8° and 9° S. Here particles are accu-ated in the euphotic zone. On the contrary, region at 4° S between Stations 205 and displays a scarsity of suspended matter cal for the convergence which exists there. distribution also shows indications of a ier particle content in the region of the iator Divergence. The particle maxima are nded in meridional direction although the nsverse circulation within the Counter-ent is relatively feeble. Phytoplankton ndrawn from the euphotic zone generally s near the maxima and the belt of conver-ce though narrow is clearly distinguished ugh the whole water column.

hus, the particle distribution clearly re-ts the structure of the water masses within system of equatorial currents in the Indian an. In this case the particle content is n more significant than other properties of water.

he interpretation of the particle distri-ion in the equatorial Pacific is more intri-. Four sections were run across the system quatorial currents but only minor parts of n cross the currents at right angles (see the ey chart). It may be emphasized that icles are transported westwards by the iatorial Currents, eastwards by the Counter-ent. As the distribution of suspended ter changes in a zonal direction it will, n increase of depth within the currents, be conform with the surface distribution ern. Nevertheless the four sections exhibit ral common features below the current on or below 300 m. In this respect Sections -80 and 80—93 are similar and the same lies to Sections 105—123 and 126—138. very oblique Section 58—80 as well as Section 105—123 show rather complicated features with several slight divergences and convergences. Therefore, the treatment is here limited to Sections 80—93 and 126—138 for which the typical structure of the water masses is evident.

Viewing the former section (Fig. 7) we notice that a rich plankton population is present in the divergence regions at the Equator and at the northern boundary of the Countercurrent (Station 86). On the other hand Station 89 where the main convergence takes place, displays a lower content of suspended matter. The transverse circulation within the Countercurrent is fairly intense and carries particles from the divergence towards the convergence. The trend of the isopleths and the maximum in midstratum at Station 88 indicate that a large amount of particles sinks below the Countercurrent. Furthermore the particle concentration at mid-depths is high on both sides of the Equator Divergence.

Section 126—138 is characterized by another structure (Fig. 8). The convergence takes place at Station 135 in close proximity to the Equator Divergence which is only feebly developed. In consequence, these two regions overlap, and the convergence region is also supplied with particles which are carried down with the descending water. The northern divergence at Station 129 is well defined by the distribution of particles. A corresponding particle maximum at mid-depths is found a little further to the north. It is seen that the layers below the Countercurrent except near its southern boundary are relatively free from suspended matter.

Summing up, we may say that, because of the action of transverse circulation, the particle distribution pattern at 900 m below the equatorial currents in the Pacific differs in its major features from the distribution in the surface.

In July 1948 a section was run across the system of equatorial currents in the Atlantic

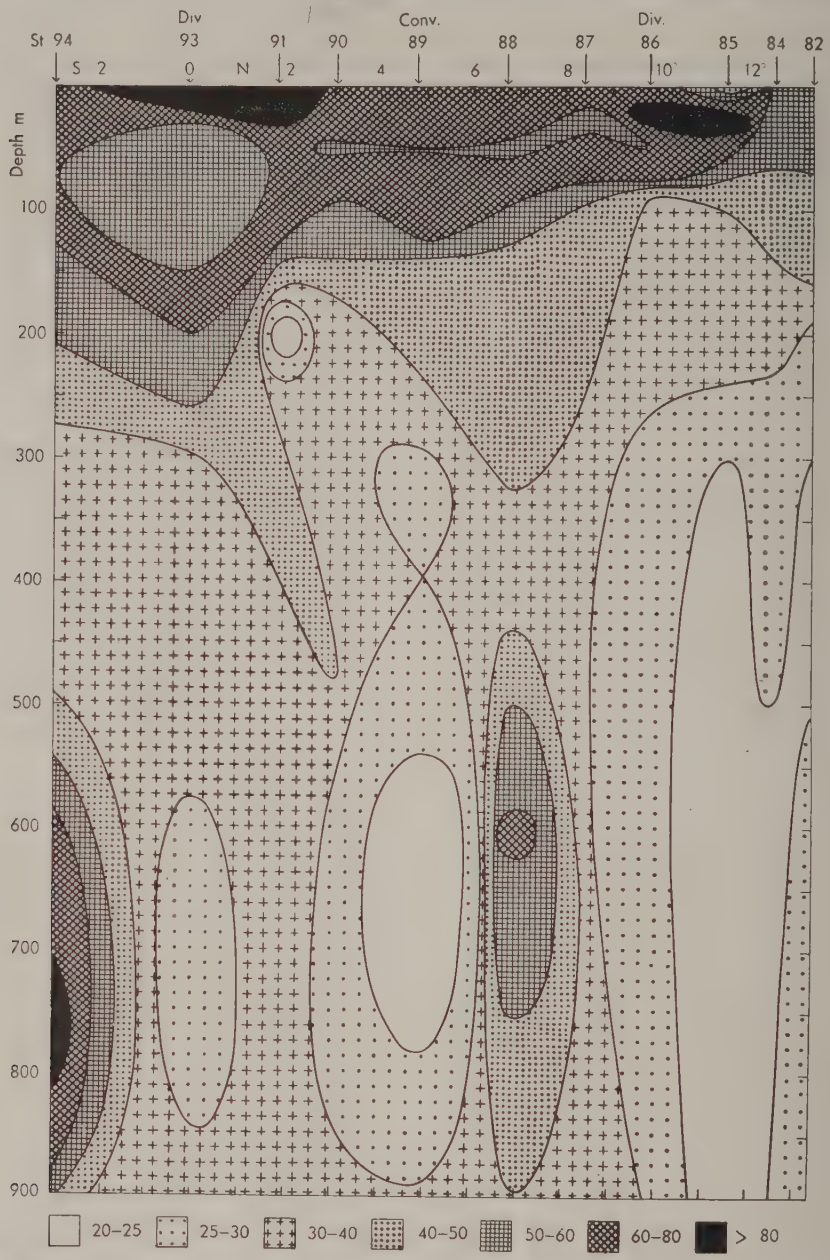


Fig. 7. Vertical distribution of particles between Stations 82 and 94 in the Pacific Ocean.

from Station 325 off the Cap Verde Islands to 337 at the Romanche Deep. A picture of the particle distribution pattern is shown in Fig. 9. The section, which barely includes the North and the South Equatorial Current has quite simple features. The region of convergence at Station 333 being near the Equatorial Divergence is richly supplied with particles.

In summer the Countercurrent often flows to the north. Judging from dynamic data far as they have yet been worked out, northern divergence occurs between Stat 326 and 327 but it is not well developed a does not appear in the particle distributi Conditions at Station 326 are influenced the upwelling along the west coast of Afr

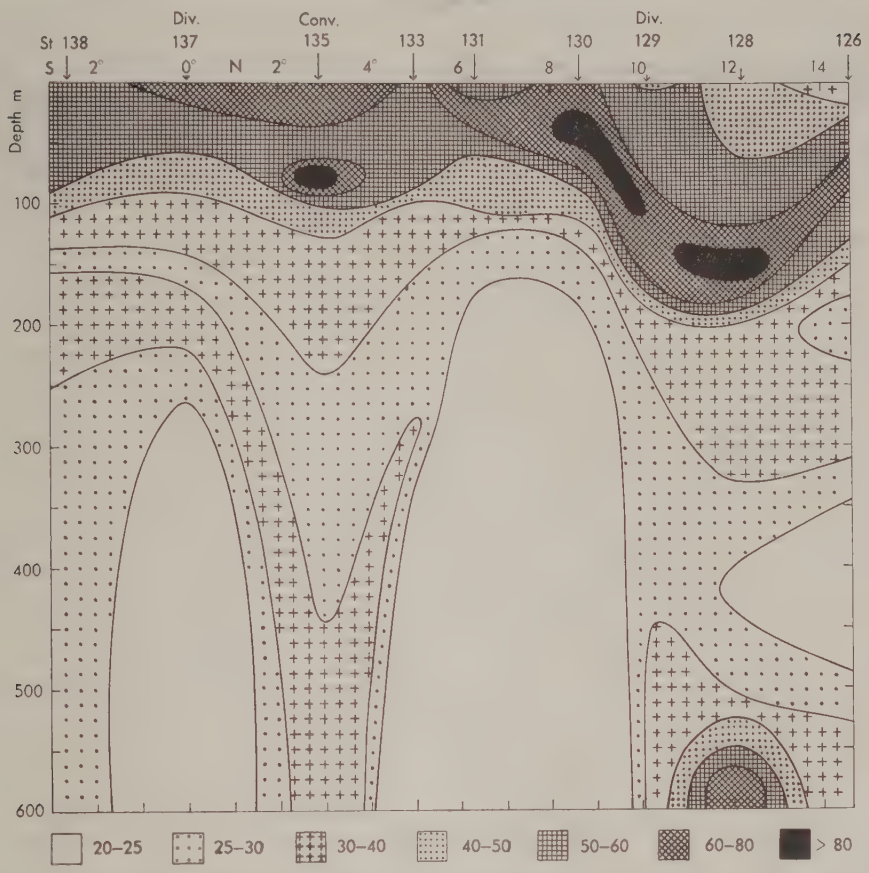


Fig. 8. Vertical distribution of particles between Stations 126 and 138 in the Pacific Ocean.

the Cap Verde tongue of plankton-rich ater (HENTSCHEL, 1928) enters already here. The phytoplankton population stands in a rtain relation to the content of nutrients id oxygen. As this discussion is chiefly nfined to hydrographic problems we shall ot subject biological questions to a close xamination but one instance is given here. t Station 128, (Fig. 8), near the northern ivergence belt, a particle maximum of living id dead plankton was present at a depth as eat as 150 m. At this locality the water down 75 m was found to be supersaturated with xygen whereas phosphate was low. Evidently, high production had taken place in the rface water at which nutrients were ex-austed.

An interesting feature in particle distribution at middepths is the conspicuous maximum that occurs between 700 and 800 m at all stations (111—123) in the section Tahiti—Hawaii. The phenomenon was also found at some other localities in the central part of the Pacific. At Station 113 the oxygen poor layer (0.75 ml/L) encountered at 600 m was narrow whereas, toward the north, minimum oxygen concentration (0.50 ml/L) was found within a larger body of water. If mean values of oxygen content and particle content between 400 and 900 m are computed for Stations 111—123 (0°—15° N) the vertical distribution curves shown in Fig. 10 come out. It is here illustrated that particles are abundant near the lower limit of the oxygen poor layer.

By decomposition of the sinking remnants of organisms the size of particles decreases

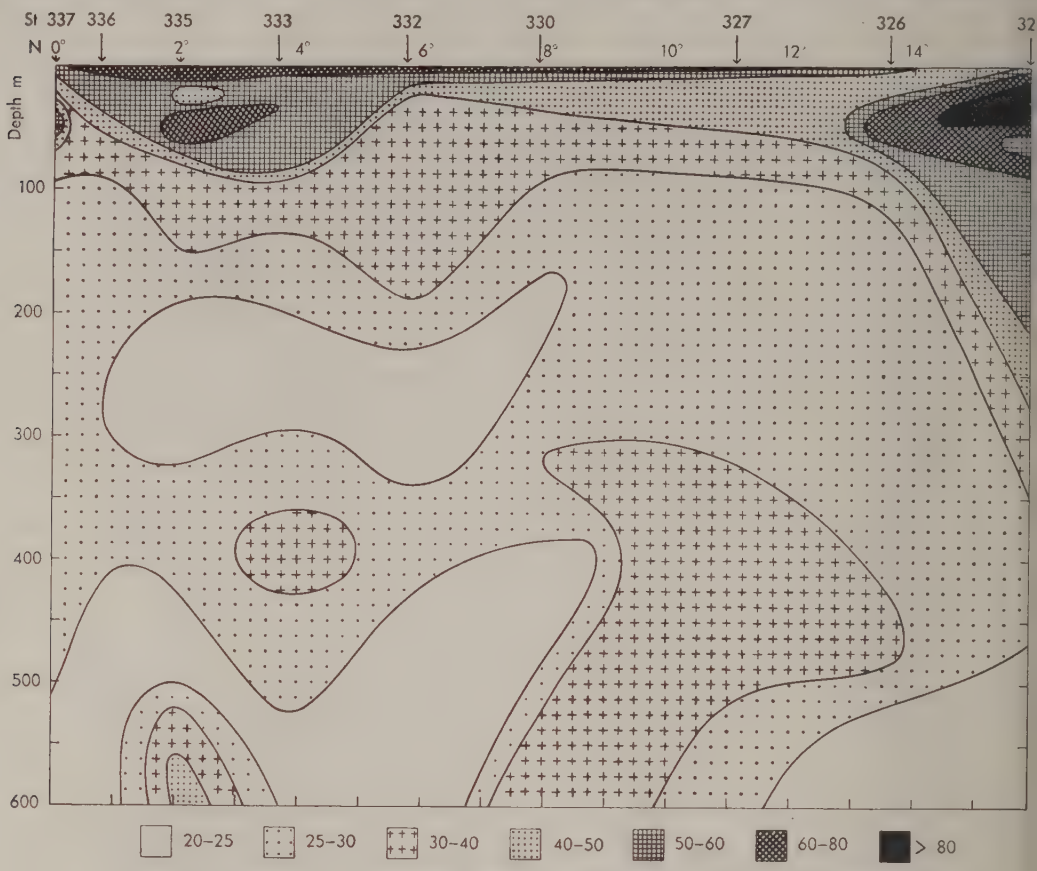


Fig. 9. Vertical distribution of particles between Stations 325 and 337 in the Atlantic Ocean.

rather rapidly with time (SEIWELL and SEIWELL, 1938) which reduces the sinking velocity. The retardation of sinking due to increase of viscosity with increase of depth must also be taken into account. On the other hand, the decay of organic debris increases the grav of particles and hence their velocity. Fina the rate of decomposition is influenced temperature becoming thus reduced tow greater depths. The result of these combi effects may eventually lead to an accumu tion of particles at some level at mid-dept The possibility of a distribution according the water density is precluded but it see probable that vertical movements are involv The ascending motion that is associated w the divergences in the upper layers may traced down to 800 m as a sluggish upw water movement.

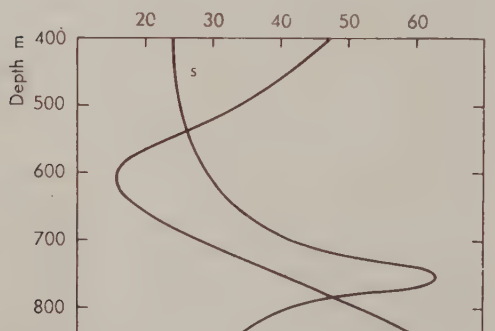


Fig. 10. Oxygen minimum and particle maximum at mid-depths. Mean values for Stations 111—123 (0°—15°N) in the Pacific Ocean.

As regards the explanation of the oxy minima in the oceans, SVERDRUP (1938) emphasized that the consumption of oxy must equal the replenishment at all lev In consequence, the oxygen minimum can

ascribed to minimum replenishment nor maximum consumption. Since ZoBell 940) has shown that the rate of oxidation of ganic matter as indicated by oxygen con- mption by bacteria is practically independent the oxygen tension, it appears that no ar relationship exists between the vertical stribution of oxygen and of organic matter. However, Redfield (1942) has assumed at in the tropical Atlantic a large part of the served phosphate concentration and oxygen ficit must be attributed to the decomposition organisms which have sunk from the sea rface down to depths as great as 600—800 m. the Pacific section considered in Fig. 10 plenishment of oxygen through advection ust be low as the horizontal water movements e slow at mid-depths. Evidently, the vertical stribution of oxygen must be largely governed y the presence of organic matter. Slight axima in phosphate and carbon dioxide at ie particle maximum at 760 m indicate that rganic matter is there oxidized to a greater xtent than at the oxygen minimum 150 m igher up. This would mean that the lower vel is more liberally supplied with oxygen presumably from below, so the above assumption of a slow upward water movement is borne out.

Survey of the Upper Strata

So far the results from the upper strata have been examined in view of special problems. The meridional distribution across the equatorial currents has already been studied in some detail. It now remains to survey the main features of the zonal particle distribution. For dynamical reasons vertical sections along the Equator are most suited to illustrate the variations in suspended matter from east to west. In addition, some observations from marginal or adjacent seas not yet discussed are included in the survey.

The particle content is reflected by the extinction of daylight in the ocean. Some Tyndall measurements have served to interpret the scattering problems of the subsurface radiation (v. III, no. 1). As mentioned the Tyndall unit is based on measurements with the transparency-meter. On the whole, the computed s-values are consistent with results

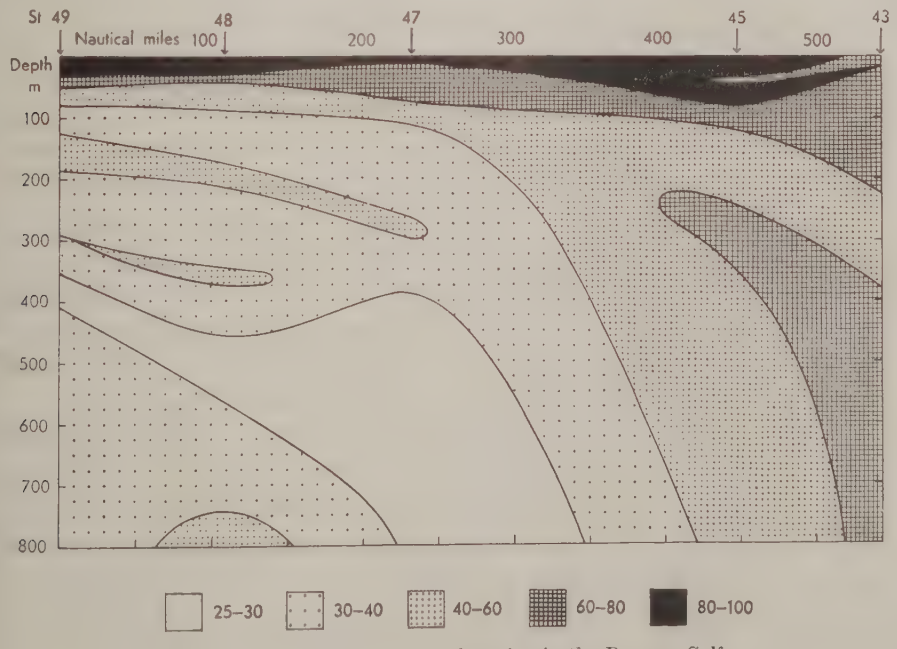


Fig. 11. Particles in a vertical section in the Panama Golf.

from other light measurements during the expedition.

Viewing a vertical section of the particle distribution in the Panama Gulf (Fig. 11), its most conspicuous feature is the high turbidity of the whole water mass near land (Station 43) which is chiefly due to a large supply of terrigenous material. There is an abundance of suspended matter in the surface water of the Gulf which is a region of high productivity. The ready supply of nutrients to the euphotic layer supports the plankton production which is also favoured by the high stability. The very marked discontinuity surface between 25 and 50 m to some degree governs the distribution of the plankton. Referring to the above discussion, there is no clear relationship between the particle content and the pronounced oxygen minimum at 300—500 m.

The high fertility of the Galapagos area is illustrated at Stations 49, 52, 55, and 58. Station 49 near the Equator is somewhat lower in particle content than the others, due to the Equator Divergence being not as well developed to the east as to the west of the islands. The abundance at Stations 52 and 55 near 3° S indicates that these localities are influenced not only by the Equator Divergence but even more by a supply of highly fertile water from the upwelling area off the coast of Peru. The actual stations also display maximal contents of phosphate. Thus, there

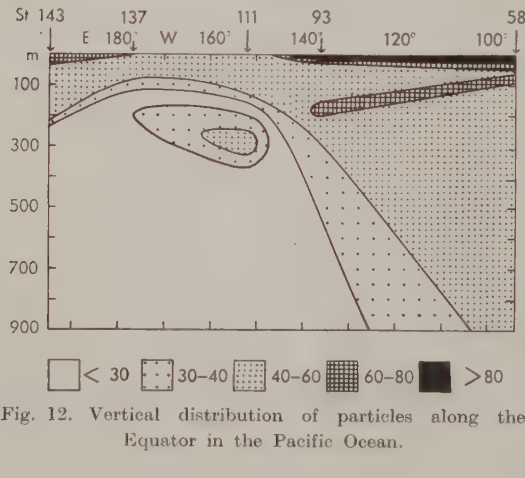


Fig. 12. Vertical distribution of particles along the Equator in the Pacific Ocean.

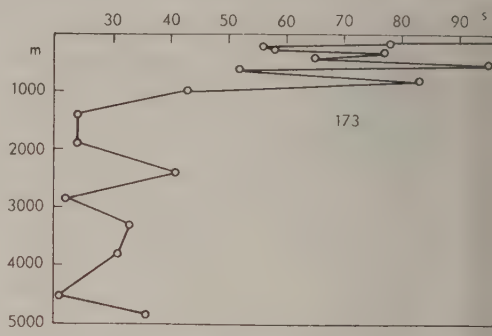


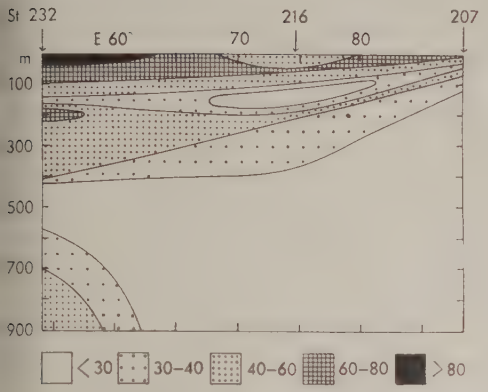
Fig. 13. Particle content in the Flores Basin (Station 173).

is a confluence of favourable factors de mining the production in this region (Sverdrup *et al.*, 1946, p. 112).

A vertical section of the main features particle distribution along the Equator within the South Equatorial Current in Pacific is presented in Fig. 12. To the w from Station 58 the plankton density gradu diminishes and the water at greater dep gets accordingly clearer. Station 137 at 177° is most barren of particles whereas further the west the content is again higher. T distribution is naturally related to the dis bution of nutrients but to some degree it m be affected by the scarcity of terrigen material in the middle of the ocean. Am other stations on the route of the »Albatr in the western Pacific the deep Station off Mindanao is fairly rich in particles, y not comparable with the eastern areas.

The next hydrographical station (173) oc pied in the Flores basin exhibits an abunda of matter in the upper strata and, in additi a pronounced stratification in the distribut (Fig. 13). Further attention will later be gi to this station.

An equatorial section in the Indian Oc from observations in March and April 1 shows a stratified structure (Fig. 14). Stat 216 is definitely higher in phosphate cont than Stations 207 and 232. Yet the latte most rich in suspended matter. But the h oxygen content suggests a high production



g. 14. Vertical distribution of particles along the Equator in the Indian Ocean.

e upper layers which have been depleted of utrients. The vertical distribution of plankton d the conditions for plankton production the north-western areas of the Indian Ocean ve been closely studied by GILSON (1937). The central part of the Red Sea in the ring 1948 was characterized by a small nount of particles. Here a certain supply of ind-borne sand occurs but the sinking grains end a relatively short time in the sea.

Similar conditions were met with in the eastern and central part of the Mediterranean. In particular at Station 272 low values were found ($s = 50$ in the euphotic layer) which is consistent with the high transparency and the brilliantly blue colour of this water. In the western Mediterranean conditions are more favourable for phytoplankton production and the measurements reveal rich populations in the upper strata.

The Atlantic Ocean shows large horizontal variations in particle distribution, and we there encountered maxima as well as minima. In the upwelling area along the west coast of Africa at Station 322 an s-value of 250 for the first 30 m was observed (Cf HENTSCHEL, 1928) whereas the Sargasso Sea at Station 371 is represented by $s = 40$ for the uppermost 100 m. From the Sargasso Sea the content of particles increases rapidly to the north. At Station 400 it is much higher than the normal value for the equatorial areas.

At last we consider a vertical section from Martinique to the central parts of the Carribean Sea (Fig. 15). According to oceanographic data one branch of the North Equatorial Current

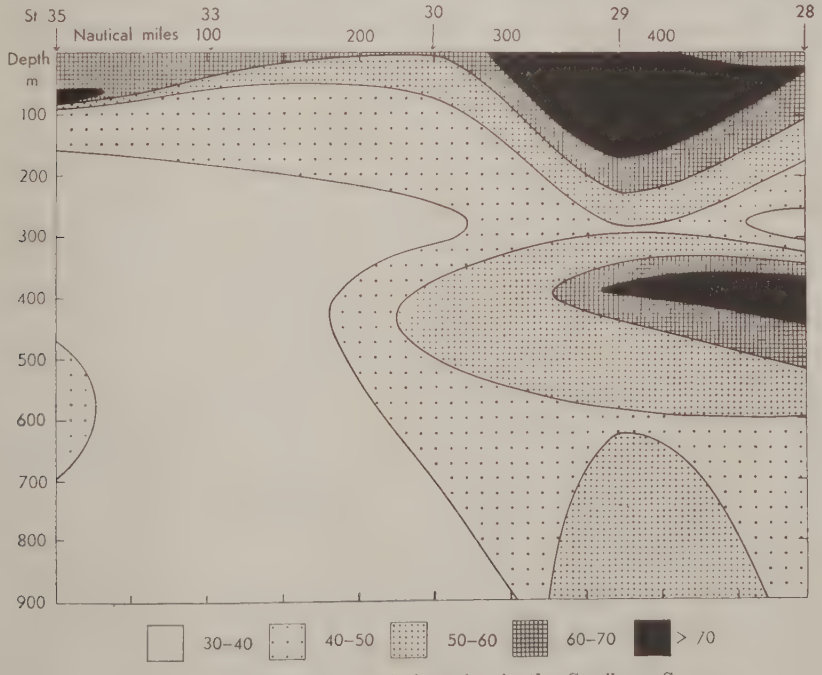


Fig. 15. Particles in a vertical section in the Carribean Sea.

flows into the Carribean Sea, where it is mixed with water of South Atlantic origin (SVERDRUP *et al*, 1946). Obviously, turbid water of the latter type is present in the upper layers at Station 29 which is in conformity to the measurements of subsurface daylight (v. III, no 1). The section is apt to demonstrate the intense mixing between the two water masses that takes place in the Carribean Sea. Finally it is mentioned that the particle distribution at Station 39 (11° 34′ N, 78° 41′ W) in the western Carribean Sea is similar to that at Station 35.

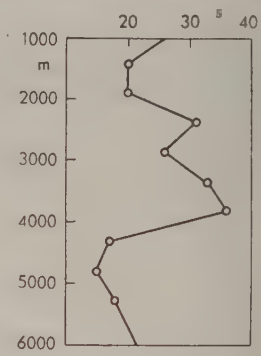


Fig. 16. Particle content between 1 000 and 6 000 m the Romanche Deep (Station 340).

Deep Water

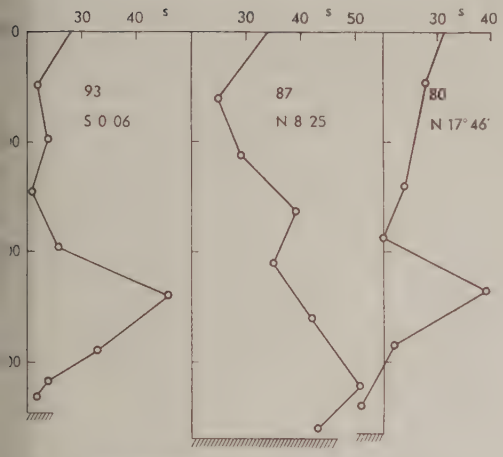
The treatment of the upper layers has been limited to the water column between surface and 900 m. The particle distribution is, however, also indicative of deep currents and may, sometimes serve to distinguish and characterize different water masses. A typical illustration is given for the Flores basin (Fig. 13). Here particles are abundant in the upper layers. A conspicuous decrease of the *s*-value between 800 and 1400 m suggests the inflow of another mass of clearer water. According to results of the Snellius expedition (VAN RIEL, 1934) a current is passing between 1400 and 1800 m from the Pacific over the different sill depths to the Flores basin. This current supplies the basin with fairly clear deep water.

Another graph is given in Fig. 16 for the Romanche Deep in the Atlantic Ocean. Cold Antarctic Bottom Water from the Brasilian basin flows over the sill depth at 4100—4400 m and mixes with the North Atlantic Deep Water (BÖHNECKE, 1927). The presence of a new water mass is indicated by a strong decrease in particle content at 4000 m. The temperature is correspondingly diminished from 2°.3 to 1°.1.

Though the particle content can be equal and even superior to other identifying properties for tracing the origin and movements of water masses, it is not a well-defined char teristic of a water mass. The amount particles belongs to the nonconservative c centrations due to biological processes a sinking of particles. For instance, the meth is not suitable for studying the spreading water over long distances. But it is frequen useful as an additional identifying property supplementing and corroborating results.

The sedimentation on the ocean floor intimately connected with the quantity a the settling of particles in deep water. should again be emphasized that the rate sedimentation is not simply proportional to t measured amount of suspended material in t deep sea. The distribution of particle size the water differs considerably from that in t sediment. The particle content represented the scattering value *s* generally includes a sm amount of the big particles whereas mater of coarse texture often constitutes a consid able part of the sediment especially of glo gerina ooze.

Let us return to the subject of equator currents and consider the influence of de currents on sinking particles. The mechani associated with the equatorial currents in t upper strata of the East Pacific apparen leads to a certain accumulation of mat below the Countercurrent (Fig. 7). Con tions in deep water are illustrated by th vertical distribution curves in Fig. 17. Stat



. 17. Vertical distribution of particles in deep water Station 80 (North Equatorial Current), at Station 87 ountercurrent), and at Station 93 (South Equatorial Current).

in the North Equatorial Current is poor in rticles, whereas Station 87 in the Counter- rrent is surprisingly high, in particular near e bottom. Below the equatorial region cation 93) there is a maximum at 3,500 m t the particle content decreases towards the ttom. ARRHENIUS (v. V) has examined the lbatross» cores from this section (Stations —93) and found that the rate of deposition high below the Equator region and the ountercurrent. This implies no contradiction the particle distribution, considering that a rge amount of relatively big particles is pro- uced in the water and predominates in the diment.

The deep circulation in the eastern Pacific pears to be too slow to have any marked fect on the big-sized particles which sink pidly. CORRENS (1947) has found that the me is the case in the Gulf of Guinea where ly the strong surface currents influence the stribution of sediment. On the other hand, e fine fraction of the suspended matter can carried over long distances by the deep-sea rrents. Fig. 17 reveals that the particle ntent including mostly fine material is not iformly distributed in deep water.

It is not advisable, however, to base a discussion of Pacific sediments only on the surface distribution of suspended matter or on the positions of divergences and convergences. For, as we have seen, a certain meridional displacement occurs already in the upper strata due to the transverse circulation.

Other conditions are met with below the system of equatorial currents in the Indian Ocean. Here the number of observations is sufficient to allow us of drawing up a vertical section of particle distribution from 1,000 m to the bottom (Fig. 18). Apparently, the distribution in the upper layers, as represented in Fig. 6, still remains at 1,000 m. In deep water the amount of particles is considerably higher in the southern part of the section than in the northern part. But there is a steady tendency towards obliquity in the isopleths below 2,000 m indicating that the permanent deep current carries the sinking matter to the north. According to the general concept of the deep-sea circulation in the Indian Ocean, the intermediate water and the bottom water flow to the north, whereas water returns to the south as deep water (SVERDRUP *et al.*, p. 750, 1946). The particle distribution in Fig. 18 suggests that there is a net transport to the north. In any case the conclusion is warranted that the rate of sedimentation of small particles is higher below the Countercurrent than below the equatorial region.

The particle maxima in the deep sea are, as a rule, accompanied by slight minima in phosphate. It is well-known from limnology that suspended matter adsorbs substances dissolved in the water, in the first place phosphate (GESSNER, 1934). The phenomenon, already observed by KALLE (1939) is illustrated in Fig. 18 for the Indian Ocean and in Fig. 25 for the Atlantic.

Apart from the changes in particle distribution caused by the deep water circulation, the particle content in the deep layers is on the whole proportional to that in upper strata. Generally speaking, the East Pacific contains

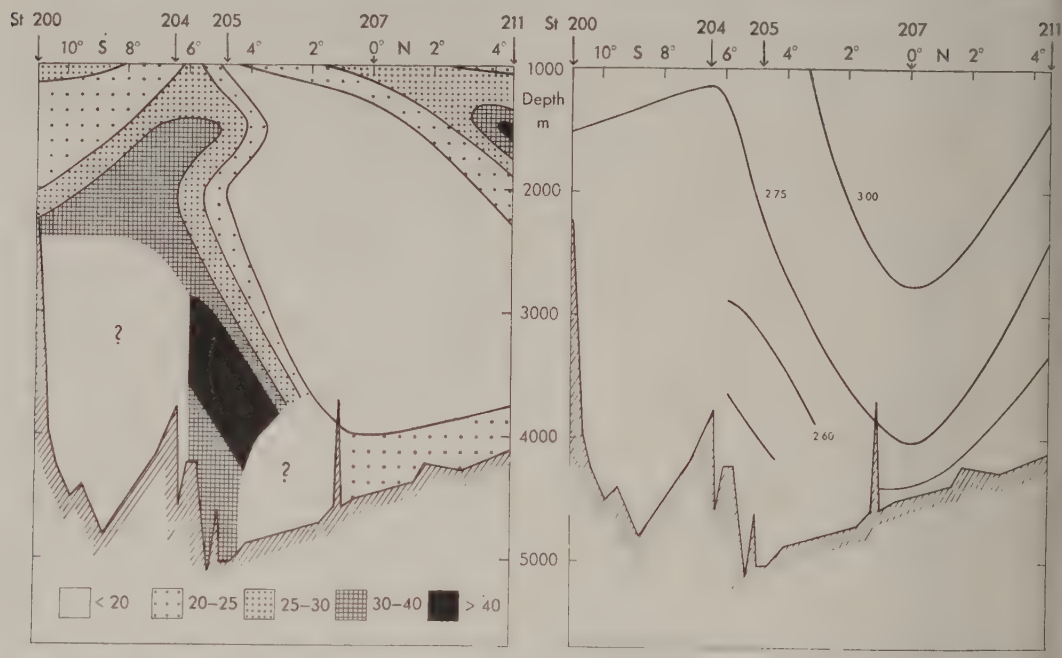


Fig. 18. Vertical distribution of particles and phosphate in deep water between Stations 200 and 211 in the Indian Oce

more suspended matter in the deep water than the West Pacific, and the East Atlantic more than the Sargasso Sea. A special interest is attached to the clearest water encountered in the oceans. The Pacific shows very clear water in its western part at about 4,000 m. ($s = 13$). In the Indian Ocean s-values as low as 14 were obtained for Station 190 around 4,000 m, but the same clarity occurs at Station 225 at 2,000 m. As regards the Atlantic Ocean it is already pointed out that layers of low particle content are present in the Romanche Deep (Fig. 16). Another equatorial Station, 347, presents similar features. Extremely low particle values were not found in the deep Sargasso Sea where the suspended matter is very uniformly distributed. At Station 273 the average s-value between 1,000 and 5,900 is as low as 22.

Water Layers Close to the Ocean Floor

The water sampling from layers close to the bottom was made by means of a new technique closely described in v. III, no. 4. The method enabled us to take water samples at small, definite heights over bottom, usua at 4, 10, 16, 25, 50, and 150 m. When the hea weight attached to the end of the wire ro reaches the bottom and then is raised 2 m so sediment could be brought into suspensi It did not appear improbable that the low water bottle fastened to the wire 1 m above t weight may accidently enclose contaminat water[1]). For instance, it is difficult to say the suspension close to the bottom at Stati 349 is inherent in the water or due to bott sediment. But the disturbing effect cann extend as far as to the next water bottle 10 m height. During the measurements d cussed below the water bottles were kept their given height over bottom to within 1 m.

The collecting of water samples at levels n the ocean floor was started in the Indian Oce where results were obtained from 7 m abo the bottom. The technique having thus be proved to function well for its purpose, t

[1]) This objection is not urged against measureme in the Indian Ocean for which the distance betw water bottle and weight was 4 m.

antic floor could be approached as close as
1.

The conditions of transport of sediment in
ocean are intimately connected to the
ount and distribution of material in sus-
sion above the bottom. The present meas-
ments will contribute direct experimental
dence in this matter. Several aspects of
transportation problem have been given
e.g. CORRENS (1939), TRASK (1939), SVERD-
et al (1946), and KUENEN (1950). Some
their basic concepts founded on the distri-
ion of sediments are referred to for the
owing discussion.

The permanent currents and the tidal currents
the bottom are likely to be weak whereas
rents associated with internal waves may
ain a considerable strength. The finest
tions of sediments may retain in suspension
at very small velocities and carried over
g distances even if the velocity decreases
some degree (HJULSTRÖM, 1939; FLEMING
REVELLE, 1939; INMAN, 1949). The influ-
e of bottom topography on the transpor-
ion is stated in the following quotation from
VELLE and SHEPARD (1939): »Transporting
ncies over the bottom depend to a much
ger degree on the bottom configuration
n on depth. The degree of protection from
nsporting agencies at any point on the
tom exercises the most important control
r the texture of the sediments at that point.»
t is gathered that fine material in suspension
be carried over long distances by currents.
depressions and basins where transporting
nts are absent the material will accumulate.
iewing the »Albatross» measurements the
st conspicous feature is that a fine-strati-
tion appears quite close to the bottom. In
ticular, a suspension is often present in the
t tens of meters above the bottom (Stations
and 387). The highly stratified distribution
icates that the turbulence is very low. Still
turbulence is sufficient to counteract the
king of particles due to gravity, provided
that the density of the suspension increases towards bottom (KUENEN, 1950). The eddy diffusion of the bottom currents is certainly able to prevent deposition of fine material as organic and lutite, particularly at peaks or where the bottom is rough.

A bottom current of considerable velocity is obviously present at Station 254 in the Red Sea (Fig. 20). It carries a heavy load of particles in which, considering the strong increase in density towards bottom, coarse material must also be included.

There are also localities where the bottom suspension is absent and the water is extremely clear in close proximity to the bottom (Stations 343 and 362). In depressions where currents and the turbulent effect vanish such a distribution of particles is very likely to occur. On the other hand, over a ridge or a peak where the fine material is swept away by currents or even all sediment is transported away so that the bottom is uncovered, the distribution can have a similar character.

Clouds of particles were often encountered at different heights above the bottom (Stations 328, 340, 351, and 362). This indicates that the bottom suspension from adjacent rises in the bottom is distributed laterally by currents. At Station 351 (at the western slope of the Atlantic Ridge) the density of the suspension is very high, and it must be assumed that there is erosion at the higher levels due to a strong current or else that a mudflow due to slumping takes place. These conditions of a stratified particle distribution were more often met with in the Atlantic than in the Indian Ocean, due to a more irregular bottom topography, but also to a more intense deep-sea circulation in the Atlantic.

The water just below the suspension cloud is usually very clear which gives ample evidence for low turbulence. The arguments given for water layers close to the bottom also have a bearing on the following discussion. The transport mechanism that is active near the

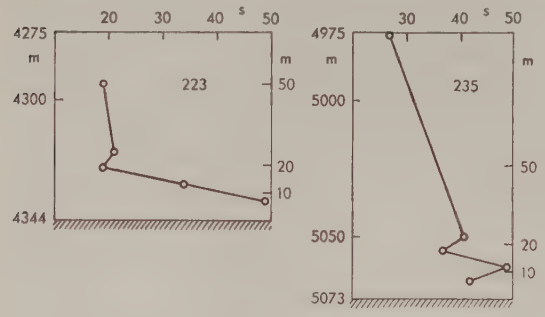


Fig. 19.

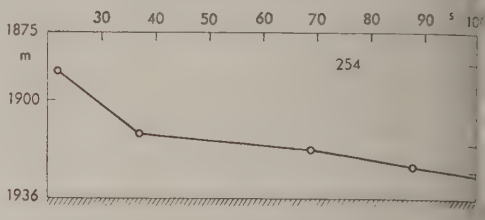


Fig. 20.

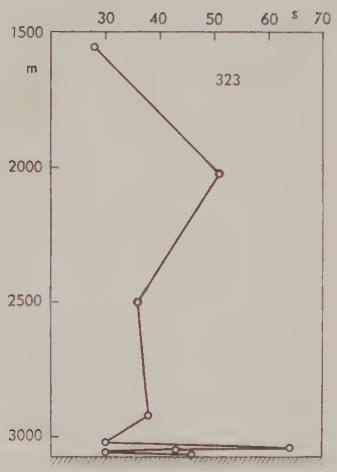


Fig. 21.

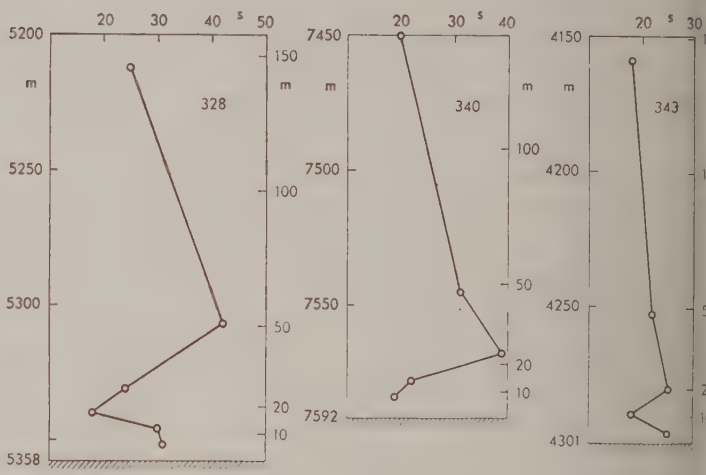


Fig. 22.

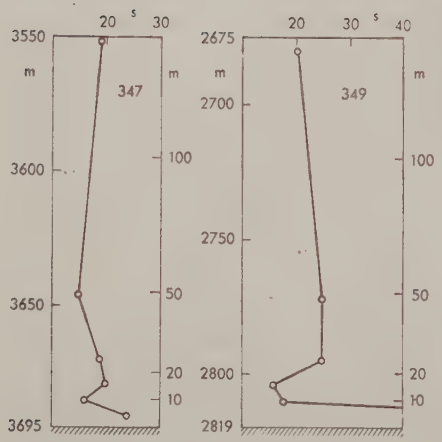


Fig. 23.

Particle distribution next to the ocean floor

at Stations 223 and 235 in the Indian Ocean (Fig. 19)

at Station 254 in the Red Sea (Fig. 20).

at Stations 328, 340, and 343 in the Eastern Basin of the Atlan Ocean (Fig. 22),

at Stations 347 and 349 over the Mid Atlantic Ridge (Fig. 23)

Particle distribution in deep water

at Station 323 in the Eastern Atlantic (Fig. 21).

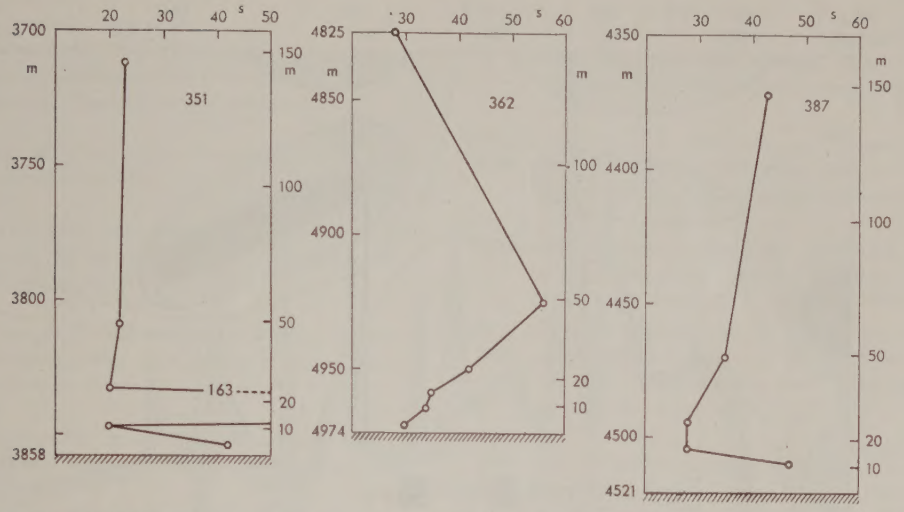


Fig. 24. Particle distribution next to the ocean floor at Stations 351, 362, and 387 in the Western Basin of the Atlantic Ocean.

ean floor is expected to operate in a much ger scale at the big submarine peaks and ges. As an instance a vertical section near e Equator in the Atlantic is shown in Fig. 25. me large accumulations of suspended matter ggest that the permanent currents carry suspensions from the higher regions of the lantic Ridge. The transporting agent may the North Atlantic Deep Water which, cording to WÜST (1936), flows across the uator to the south with a maximum velocity 8 cm/sec. It is interesting to note that the tures of the actual section support the very st measurements by KALLE (1939). In a eteor» section near 30°N he found similar xima. Kalle is, however, inclined to attrib- the particle clouds in the first place to lcanic activity on the ocean floor. Naturally h activity could carry sediment to high els chiefly through convective rising water vements although this effect must be local. is also evident that a seaquake may bring ge amounts of sediment into suspension. vertheless the chief agency for the large rizontal extensions of the particle maxima no doubt currents.

The question arises if the available material of Tyndall measurements gives some more evidence of such particle maxima in regions with an irregular bottom topography. For instance, to the south-east of Station 128 (depth 5,420 m) in the Pacific, a submarine peak rises to 2,423 m according to the Monaco chart. There is every reason to believe that a high scattering value found at 2,414 m is due to a lateral distribution of material from this ridge, which probably extends farther to the west.

On the other hand, high concentrations of suspended matter in the deep-sea was frequently encountered at localities for which there is no evidence of an irregular bottom topography. Whether also in these cases currents are responsible for the stratification remains at present an open question.

In the general field of sedimentation the transporting problems is important (cf. hypothese concerning the formation of submarine canyons) and further research on all phases of this problem is desirable. It would be be necessary to study in detail not only the distribution of debris but also the bottom topography, preferably in sections parallel to the permanent deep currents.

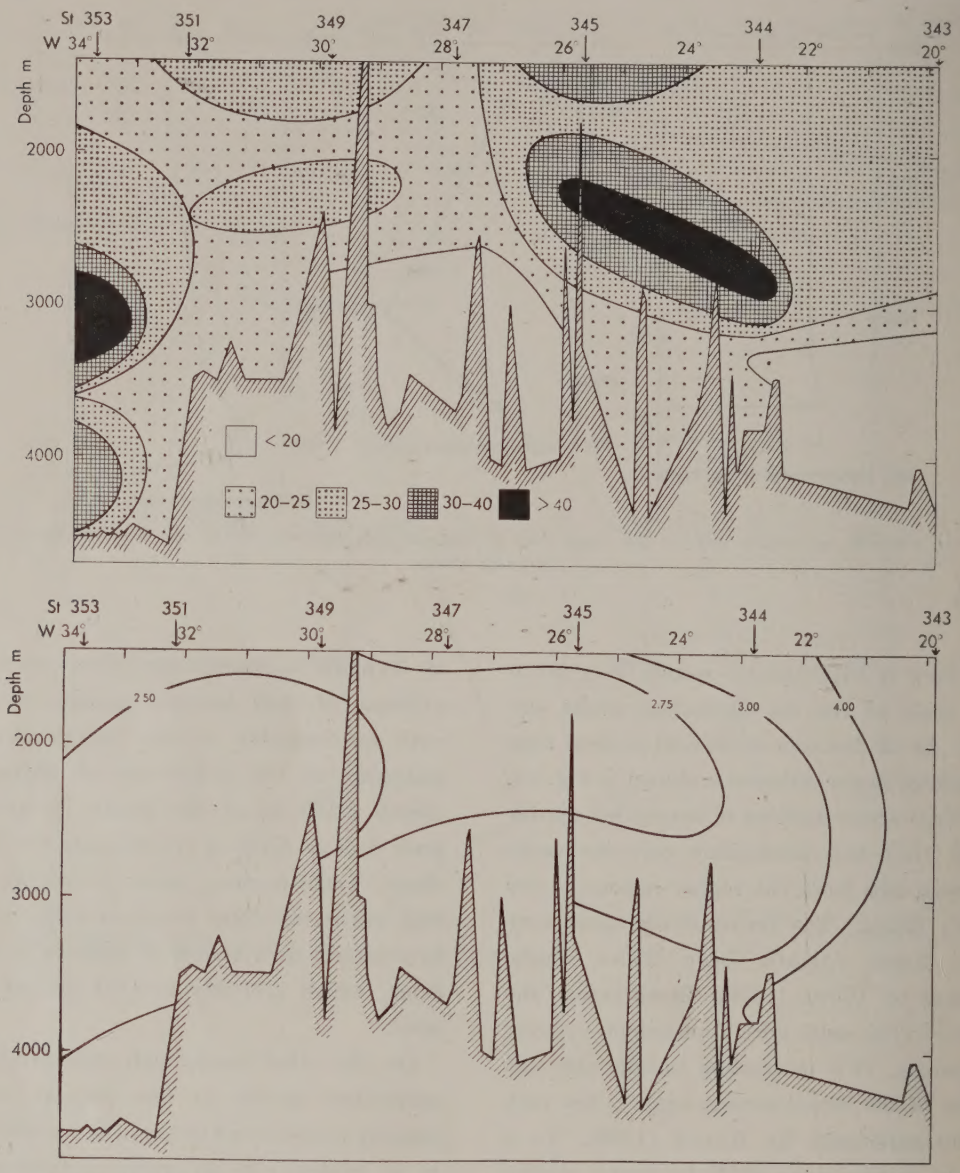


Fig. 25. Vertical distribution of particles and phosphate in deep water along the Equator in the Atlantic Ocean

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